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Research Paper

Effects of roll and flail conditioning systems on mowing and baling of *Miscanthus* × *giganteus* feedstock

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Miscanthus and switchgrass have been identified as major energy crops with high potential use for bioenergy. For example, a projection from the US Department of Energy showed that miscanthus would contribute the highest percentage of biomass feedstock as a single plant species by 2030. However, the current commercial production of miscanthus is largely undeveloped. The effect of two common conditioning systems (use of a steel roll or flail) on the harvesting and baling of miscanthus feedstock was compared through field studies. These studies were carried out in Easton, Illinois, USA and data collected included time and motion, fuel use and bale densities. The flail conditioning system performed better while mowing miscanthus crops using higher travel speed, field capacity, and field efficiency. The roll conditioning system, on the other hand, performed better when baling roll-conditioned crop windrows. Flail conditioned bales had 5% higher density than roll-conditioned ones. The information obtained from this study can be useful in predicting machine and work force requirements for miscanthus harvest, which in turn could help reduce overall monetary and energy requirements for feedstock development.

1. Introduction

The ever-increasing demand for energy and transportation fuel has resulted in several policy shifts in the USA. The two great energy crisis in 1973 and 1979 (Hamilton, 2011) were important triggers for US lawmakers to ponder on their country's energy security. The National Renewable Energy Laboratory (NREL) was established by USDOE in 1974 and it started its pioneering research on bioenergy and biofuels from 1977. A major shift in the policy, however, came in 2006 when President George W. Bush's stated in his state of the union address "*Keeping America competitive requires affordable energy. And here we have a serious problem: America is addicted to oil, which often imported from unstable parts of the world*" (Bush, 2006; Hoekman, 2009). This event also marked the enactment of Advanced Energy Initiative (AEI), which was targeted to encourage advanced technologies in energy generation by promoting the use of bioethanol derived from cellulosic plants (Milliken, Joseck, Wang, & Yuzugullu, 2007). As of 2016, the United States is the world's largest producer of ethanol with more than 70 billion litres (about 58% of world share)

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production in that year (RFA, 2016). The biofuel extracted from maize (US corn) starch accounted for 94% of total biofuel produced in the US in 2012 (USDA, 2018). Two updates from 2011 and 2016 reports have clearly emphasised the need for the US aggressively utilising energy crops such as miscanthus, switchgrass, and small-diameter perennial tree species for biofuel generation in the coming decades. In fact, the 2016 update has predicted that the energy crops will contribute more than 700 million dry tonnes of biomass feedstock by 2040 and that miscanthus will top the list (Langholtz, Stokes, & Eaton, 2016; Perlack, Stokes, Eaton, & Turnhollow, 2011).

Miscanthus $\times$ *giganteus* (giant miscanthus) is a prominent C4 crop, which, in the last decade, has been considered as one of the most valuable and efficient energy crops due to its promising properties (Heaton, Clifton-Brown, Voigt, Jones, & Long, 2004; Roy, Dutta, & Deen, 2015; Sopegno et al., 2016; Xue, Lewandowski, & Kalinina, 2017). Some of the important properties of miscanthus that makes it an ideal energy crop are minimal nitrogen input, high yield, minimal field operations, and suitability for marginal and arid lands. A comparative study done by Heaton, Dohleman, and Long (2008) for the Midwest US showed that under similar conditions miscanthus could be able to provide nearly three times more ethanol than maize grain using less nitrogen and energy inputs during field preparations. It can even outperform North American native perennial C4 grass, switchgrass in terms of growth and yield. Given that it can be more productive than other feedstock crops, the sustainable and large-scale harvesting systems for miscanthus has not been well developed and/or tested in fields. *Miscanthus giganteus* was first studied as an energy plant in Europe, where it proved to be very productive in wide range of climatic conditions (Heaton et al., 2004; Lewandowski, Clifton-Brown, Scurlock, & Huisman, 2000). However, there is little published information about miscanthus yield and availability in the US. Nevertheless, at present, it has been increasingly planted and harvested in Midwest, Northeast, and Southeast US.

Harvesting along with transportation is a crucial and expensive job in the entire supply chain of biomass feedstock including energy crops and forest products (Brownell & Liu, 2011; Judd, Sarin, & Cundiff, 2012; Koirala, Kizha, & De Urioste-Stone, 2017). Thus, a small increase in the field efficiency of harvesting systems could largely increase productivity in the end. Generally, herbaceous biomass crop harvesting may consist of different subsections namely cutting or mowing, conditioning, collecting, baling and chopping (e.g. Mathanker & Hansen, 2014). As miscanthus is a tall perennial grass species that can grow up to 3.5 m high and can give a yield of 5–55 Mg ha^{-1}, the preferable harvesting method may involve mowing, conditioning, and baling or chopping (Lewandowski et al., 2000; Liu, Grisso, & Cundiff, 2013). The special structure of miscanthus can impart issues on traditional harvesting equipment. Hence, mechanical conditioning of miscanthus has been considered as a means to change its physical properties before compressing it into desired shape and size of bales. Conditioning in this context refers to the breaking and weakening of the crop through some mechanical means such as feeding the crop through steel or rubber rollers or hitting the crop with steel flails. In theory, by weakening the crop through conditioning, it will become easier to bale, meaning that the miscanthus could potentially be harvested faster with denser bales (Fasick, 2015). Researchers have studied and proved that mechanical conditioning makes grass baling easier (e.g. Kumhála, Kroulík, & Prošek, 2007; Shinners, Barnett, & Schlesser, 2000). By doing this, the total cost from the field to refinery could be reduced. However, the scientific studies examining the effect of conditioning on miscanthus harvesting efficiency are still scarce. Mathanker and Hansen (2015) found that the large square baler experienced frequent plugging due to poorly conditioned miscanthus crops. The slatted-steel roll conditioning system was used in the study. They have suggested further studies regarding the improvement of conditioning system.

Time and motion studies are normally used to evaluate the field efficiencies of harvesting systems (Brownell & Liu, 2011; Eisenbies et al., 2014; Grisso, Moxley, Webb, Cundiff, & Sokhansanj, 2013). Generally, in the time-motion study, the mowing equipment (windrowers, rakes or conditioners), harvesting machines (balers, choppers or forage harvesters) and harvested materials collecting equipment (bale handler, field trucks, etc.) are tracked using various available devices such as stopwatch, video recorder, GPS units for locating and tracking.

The main aim of this study was to evaluate and compare two methods of conditioning systems (steel roll and flail conditioning systems) currently available for biomass harvesting. Important determinants such as fuel consumption, travel speed, time loss, bale handling, and harvesting capacities of these two systems were measured and calculated. In addition, effectiveness of conditioning and the effect of conditioning on the quality of bales by measuring bale weights, lengths, and bulk densities were also analysed. Our working hypothesis was that the choice of either of the conditioning systems could impart a significant difference on some of the aforementioned measurements. Details on conditioning systems, field settings and data analysis are explained in succeeding sections. Detailed field time and motion study results, such as time loss and bale handling are not included in this paper.

2. Materials and methods

2.1. *Field site description*

The miscanthus field site (Lat. 40.201434, Long. −89.831220) used for this field study is located in Easton, central Illinois, US (Fig. 1). The state of Illinois was one of the pioneer states in the US to establish miscanthus trial plots for scientific studies in the early 2000s (Khanna, Dhungana, & Clifton-Brown, 2008). The size of this field was 21.55 ha and was split into two sections by a centre pivot irrigation (Fig. 1). The field was established in May 2009 with miscanthus clone from the greenhouse at University of Illinois at Urban-Champaign. The first harvest took place in April 2010 which yielded 225 large rectangular bales (0.9 $\times$ 0.9 $\times$ 2.4 m) weighing approximately 363 kg each. In April 2012, the field was harvested for a second time yielding 1403 large rectangular bales with the same size. The third, and last harvesting, before this field study was carried out in April 2013. No fertilisers were applied and